HALO: A physically motivated AGN monitoring program to measure the Hubble constant

Team: Shivangi Pandey[1], Bożena Czerny[1], Amit Kumar Mandal[1], Swayamtrupta Panda[2], Vikram Jaiswal[1], Mohammad Hassan Naddaf[3], Francisco Pozo Nunez[4], and others

[1]Center for Theoretical physics, Polish academy of sciences, Warsaw

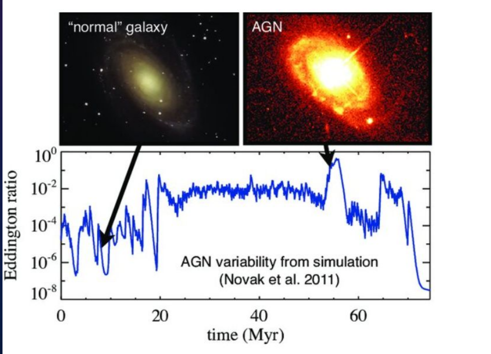
[2]International Gemini Observatory/NSF NOIRLab, Casilla 603, La Serena, Chile

[3]Université de Liège, Belgium

[4]Heidelberg Institute for Theoretical Studies

Active Galactic Nuclei

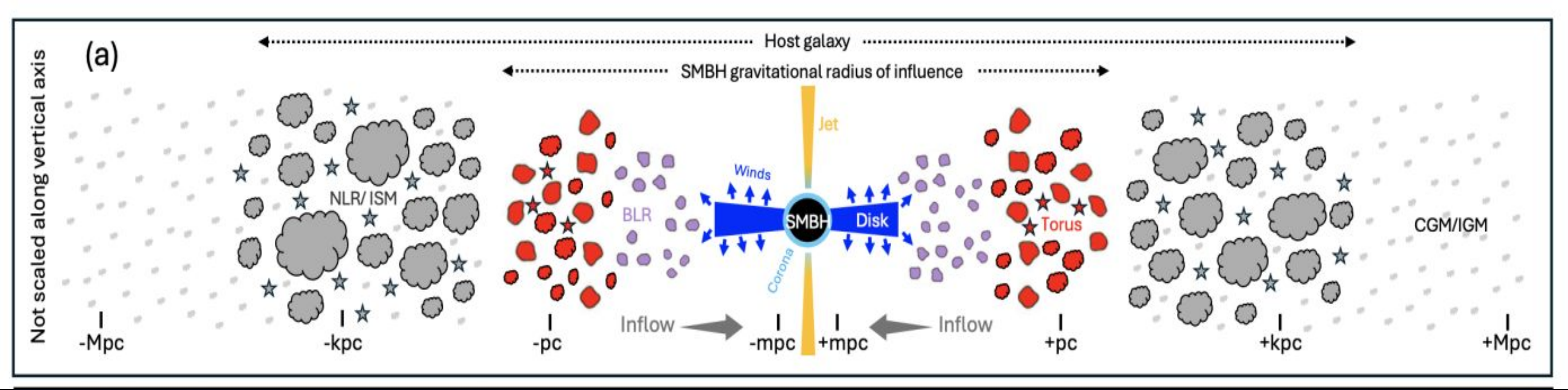
Active Galactic Nuclei (AGNs) are among the **most luminous and energetic** persistent objects in the universe. Powered by **accretion onto massive black holes (SMBHs)** at galaxy centers.



Emitting an abundant amount of radiation in a broad range of the electromagnetic region. It shows flux variation over a timescale of months to years.

The central engine is highly compact (~a few micro-arcsec) and unresolved even for low-z AGN.

Time resolution can replace spatial resolution: Reverberation Mapping



Credits: Alexander et al 2025

Part 1: Reverberation mapping(RM)

"Size and structure of AGN's components-- observing the impact of continuum variations from the central source"

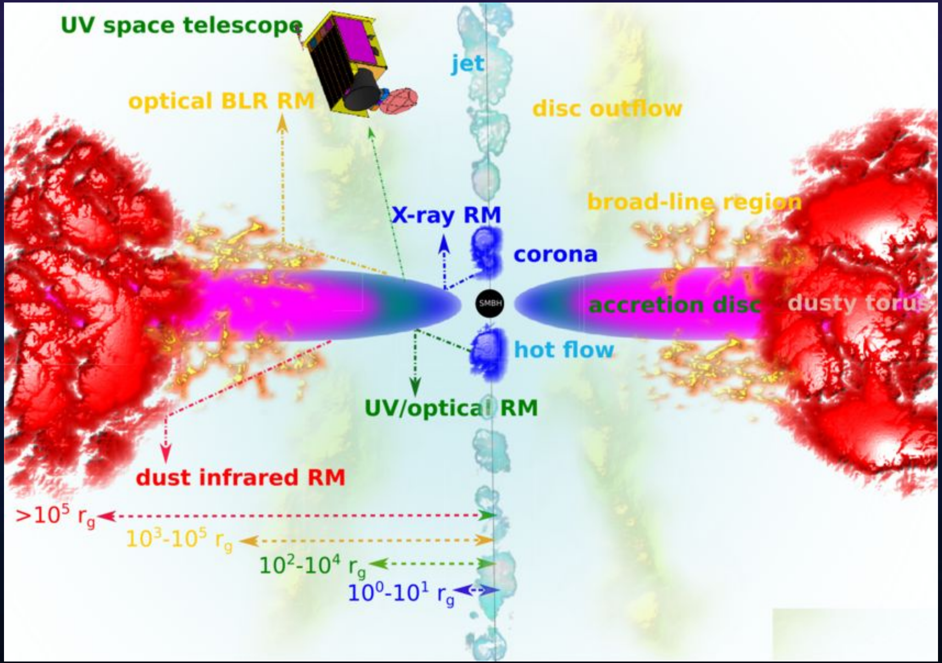


Image credits: Michal Zajacek et al. 2024 (inspired by Cackett et al. (2021))

Studying the accretion disc structure using RM through multiband observations is possible assuming the lamppost model.

A disc being irradiated by X-rays originated in the innermost central regions, e.g. corona above the disc, and the photons being reprocessed in the form of UV and optical wavelength emissions.

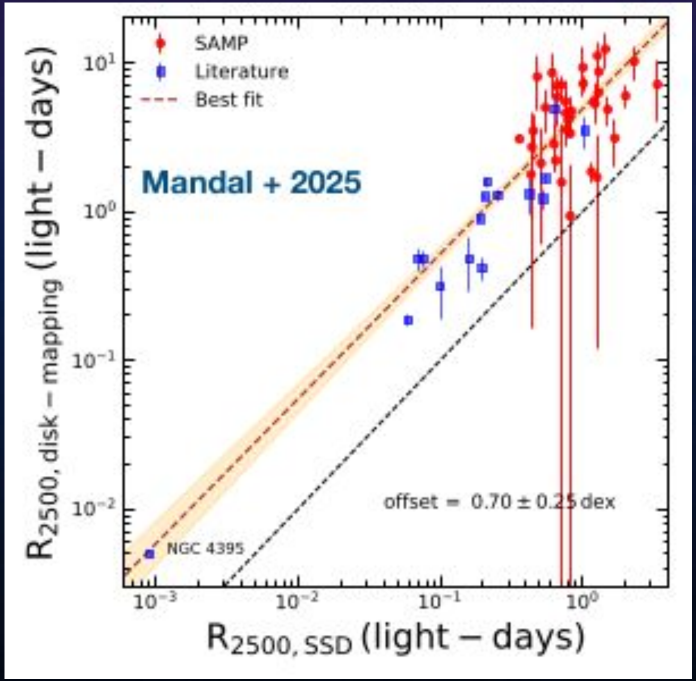
Standard Disk Model

According to the Shakura-Sunyaev model, the time lag τ scales with wavelength λ as a power law:

Accretion disc profile: blackbody type peaking at different wavelengths, simultaneous observations in multiple yield the structure and temperature profile of the accretion disc itself.

$$\tau_\lambda = \tau_0 \left[\left(\frac{\lambda}{\lambda_0} \right)^\beta - \alpha \right]$$

where $\beta = 4/3$



The Problem: Contemporary monitoring (Swift, ZTF) reveals observed lags are **3-6 times larger** than these theoretical predictions.

Continuum lags are contaminated by diffuse continuum in BLR and its emission lines

Part 2: Using the time delays to constrain the cosmology

AGNs can be used as an independent distance estimators which spans even higher redshift >7.

Based on Collier et al. 1999, Hubble constant can be measured using continuum time delays

$$H_0 = 89.6\left(\frac{\lambda}{10^4}\right)^{3/2}\left(\frac{z}{0.001}\right)\left(\frac{\tau}{\text{day}}\right)^{-1}\left(\frac{f_z/\cos i}{\text{Jy}}\right)^{1/2}\left(\frac{X}{4}\right)^{4/3}\left[\frac{\text{km}}{\text{s Mpc}}\right]$$

Cackett et al., (2007) reported H_0 based on continuum time delays of NGC 5548: H_0 =15 km/s/Mpc !!

Part 2: Using the time delays to constrain the cosmology

AGNs can be used as an independent distance estimators which spans even higher redshift >7.

Based on Collier et al. 1999, Hubble constant can be measured using continuum time delays

$$H_0 = 89.6\left(\frac{\lambda}{10^4}\right)^{3/2}\left(\frac{z}{0.001}\right)\left(\frac{\tau}{\text{day}}\right)^{-1}\left(\frac{f_\nu/\cos i}{\text{Jy}}\right)^{1/2}\left(\frac{X}{4}\right)^{4/3}\left[\frac{\text{km}}{\text{s Mpc}}\right]$$

Cackett et al., (2007) reported H_0 based on continuum time delays of NGC 5548: H_0 =15 km/s/Mpc !!

AGN monitoring project: HALO

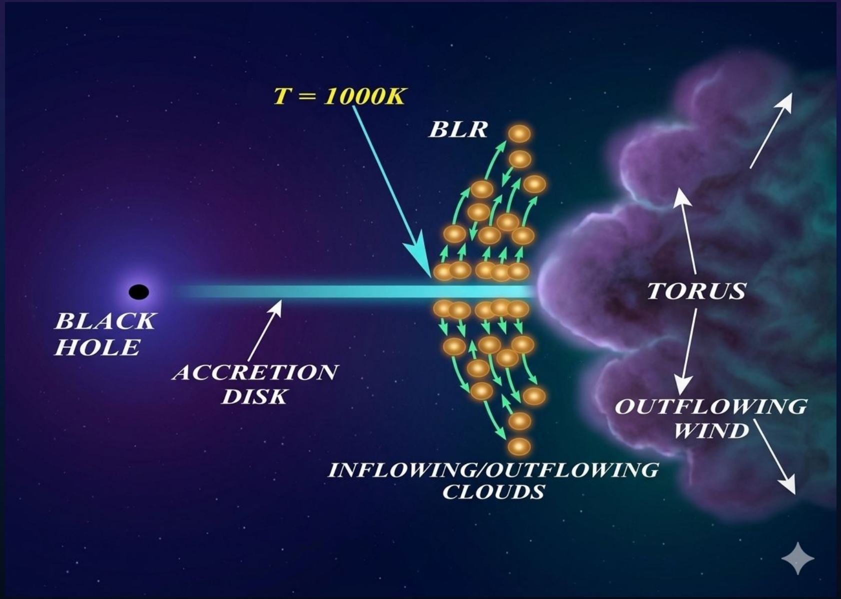
HALO: Hubble constant constraints through Agn Light curve Observation
Hubble constant estimation via lag-spectra and SED modeling by understanding the physical origin of inter-band time delays within the accretion disk.

$$H_0 = z \cdot \frac{c}{D_L}$$

D_L → Absolute Luminosity → Size of each component of AGN

How we measure absolute luminosity?

Properties of the accretion disks were formulated by Shakura & Sunyaev (1977). But the basic properties of the cloudy region (BLR) were proposed by Czerny & Hryniewicz (2011).



Dust condensation in the atmospheres of AGN has been suggested as the origin of the broad line region, where the increase in opacity from complete dust condensation yields a dramatic increase in radiation pressure that can exceed the local strength of gravity.

This temperature is independent of accretion rate and black hole mass.

Recent work by Owen and Lin 2026, 2D simulations are representative of the Failed Radiatively Accelerated Dusty Outflow (FRADO) model(e.g. Naddaf et al. 2021; Naddaf & Czerny 2022; Naddaf 2024).

The FRADO (Failed Radiatively Accelerated Dusty Outflow) model enables disentangling disk and BLR lags.

How we measure absolute luminosity?

I. Theoretical Framework: SSD+BLR Physics

- Modeling 3D cloud evolution by balancing Keplerian gravity against non-linear radiation pressure on dust.
- Thermodynamic Phase Transitions: Mapping the sublimation radius where T_{eff} (1000–1500 K) allows for dust condensation and grain survival.
- Radiative Transfer(CLOUDY): Solving the transfer equation for photon absorption, scattering, and re-emission within optically thick, clumpy media.

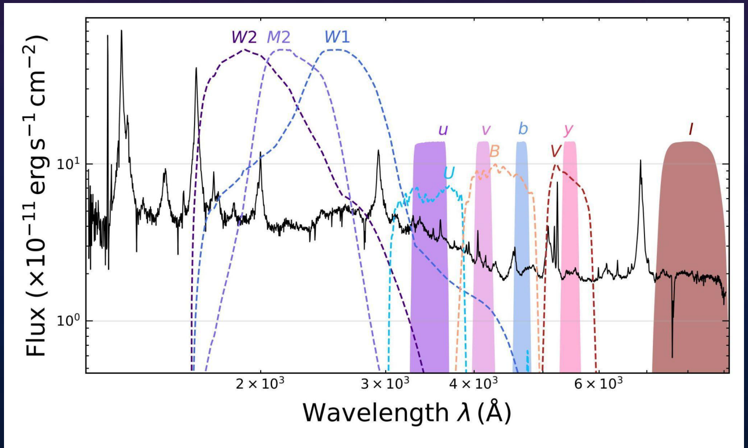
II. Predictive Outputs: Spectral & Temporal Synthesis

- Broadband SED: Simulating the full electromagnetic spectrum, including thermal disc emission and the reprocessed infrared "dust bump."
- Reverberation Lags: Quantifying time delays between central X-ray emission and BLR reprocessing to map the system's physical scale.

Distance measurement: comparison of the observed spectrum and the observed time delays to the model. Best fit gives the best absolute luminosity.

AGN monitoring project: HALO

- ★ Initiated HALO project in 2024 with OCM observatory in Chile having 60cm telescope
- ★ Photometric monitoring: us, vs, bs, ys (Strömgren filters), Ic (Johnson-Cousins)



Source Name	z	$M_\odot$	L_{BOL} (erg/s)	R_{EDD}	References
NGC 5548	0.0171	$\sim 5.2\times10^7$	$\sim 1.2\times10^{44}$	$\sim 0.02-0.04$	Bentz et al. (2015); Jaiswal et al. (2025)
Fairall 9	0.0470	$\sim 2.5\times10^8$	$\sim 1.5\times10^{45}$	$\sim 0.05-0.08$	Bentz et al. (2015); Mandal et al. (2025)
NGC 3783	0.0097	$\sim 3.0\times10^7$	$\sim 3.0\times10^{44}$	$\sim 0.08-0.10$	Bentz et al. (2015); Peterson et al. (2004)

New software[H0RIZON-AGN] for continuum time delays

Fixed externally model parameters:

- ★ Density, column density and metallicity of representative BLR cloud (10^{11}, $3x10^{23}$,5)
- ★ MBH (e.g. from the line width and delay of Hβ)
- ★ Viewing angle (40 deg for NGC 5548, 35 deg for Fairall 9)

Fitted parameters:

- ★ Luminosity distance D_L
- ★ Lamp Post height H
- ★ Eddington ratio, L_{Edd}
- ★ Transition radius between the outer cold disk and warm corona, R_{tr}
- ★ Covering factor by the BLR, CF_{BLR}
- ★ Optical depth of the warm corona, τ
- ★ Temperature of the warm corona, T_{cor}
- ★ Covering factor by the torus, Cf_{torus}
- ★ Starlight contamination

This model is based on large number of free parameters! And to model Fairall 9, we had to introduce **one more parameter** – covering factor of the dusty torus – and **one more effect** – scattering of X-rays by the warm corona!

Continuum Time-Delay Fitting: Toward a Complete Picture

From disk modelling

From warm corona

Using FRADO model

From BLR

From dusty torus

$$\Psi_{\rm tot}(\lambda,t) = \psi_d(\lambda,t) + \epsilon_{\rm PL}(\lambda)\psi_{\rm WC}(t) + f_{\rm BLR}\epsilon_{\rm BLR}(\lambda)\int_{t_0}^{t_{\rm max}} \psi_d(\lambda,t-t')\psi_{\rm BLR}(t')dt' + f_{\rm dust}\epsilon_{\rm dust}(\lambda)\int_{t_0}^{t_{\rm max}} \psi_d(\lambda,t-t')\psi_{\rm dust}(t')dt'$$

Computed from CLOUDY

With $T_{\rm dust} = 1500$ K

For BLR modelling: **F**ailed **R**adiatively **A**ccelerated **D**usty **O**utflow (**FRADO**)

$\Psi_{tot}(\lambda,t)$: Total transfer function

ψ_d: disk response function

ψ_{WC}: warm corona response function (half Gaussian)

ψ_{BLR}: BLR response function from FRADO

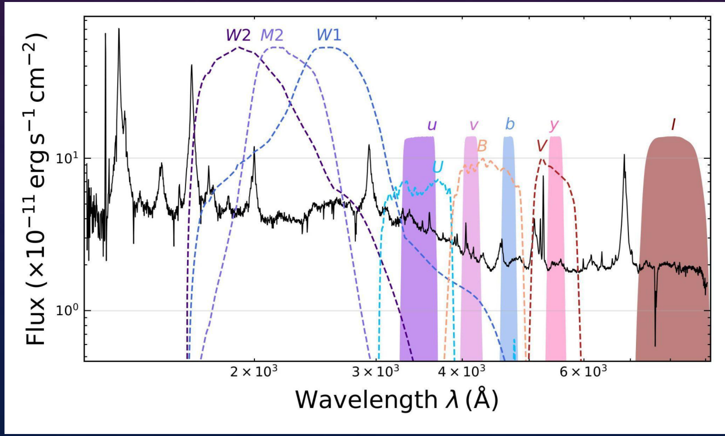
ψ_{dust}: Torus response function (half Gaussian)

$\epsilon_{PL}(\lambda)$: hard X-ray power-law

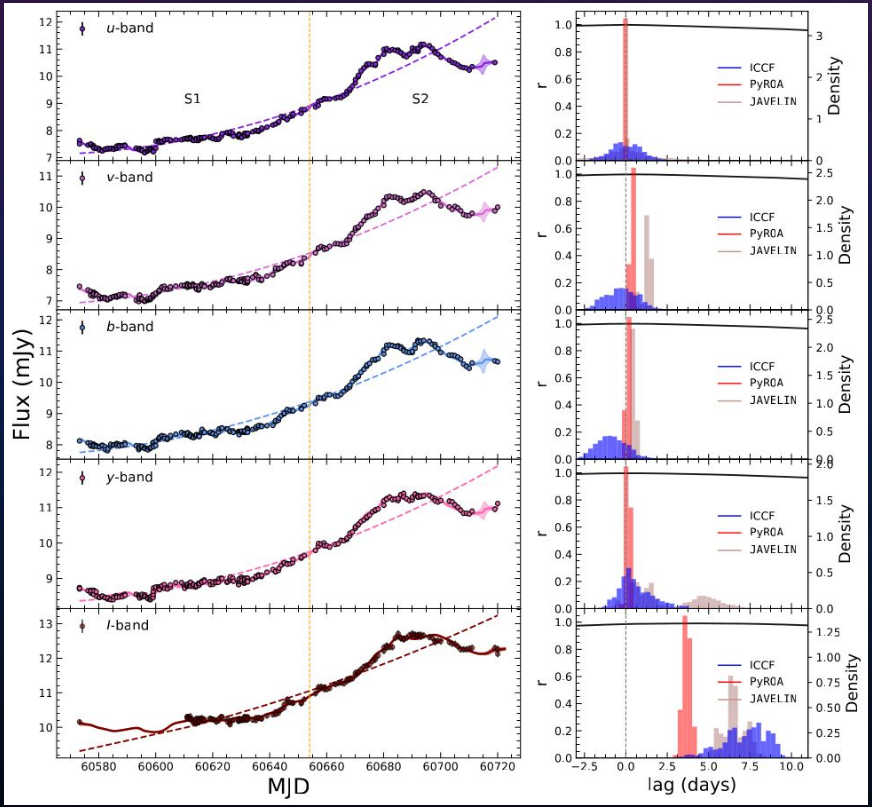
$\epsilon_{BLR}(\lambda)$: emissivity profile from CLOUDY (BLR)

$\epsilon_{dust}(\lambda)$: emissivity profile for torus

Results for Fairall 9



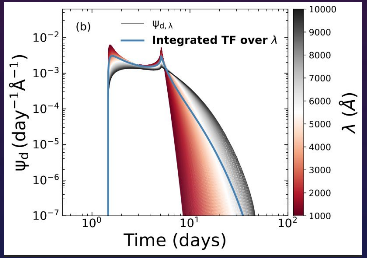
UV and optical spectra of Fairall 9 obtained with the HST Faint Object Spectrograph on 1993 January 21 and with the ESO 1.5 m telescope on 1994 July 14, respectively. Overplotted are the transmission curves of the OCM filters (u, v, b, y, and I) used for photometric observations in our HALO program, along with the transmission curves of Swift-UVOT filters (W2, M2, W1, U, B, and V) employed in constructing the photometric light curves in the literature.

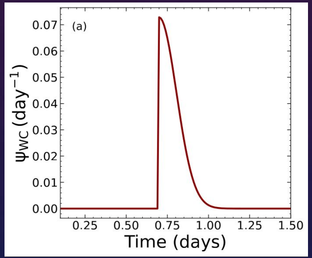


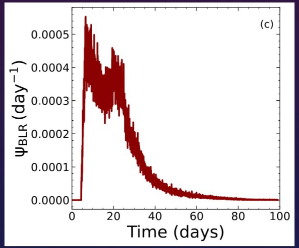
Mandal et al., 2026, A&A, 706, A176

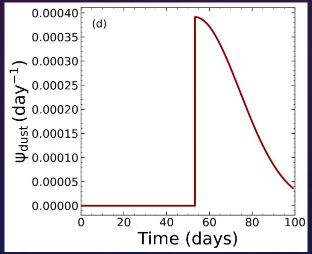
Lag analysis: ICCF (primary), PyROA and JAVELIN

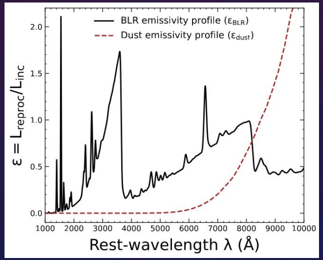
FAIRALL 9: results



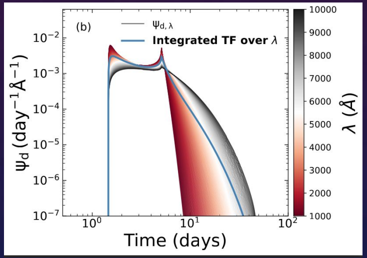


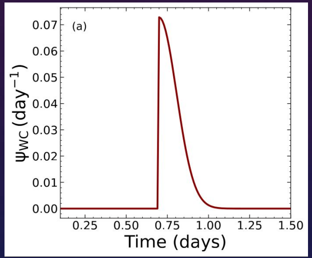


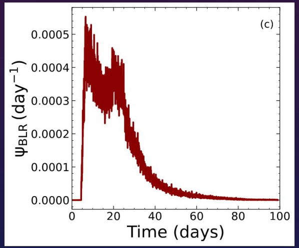


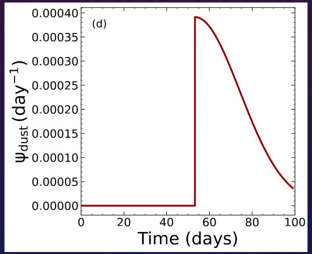


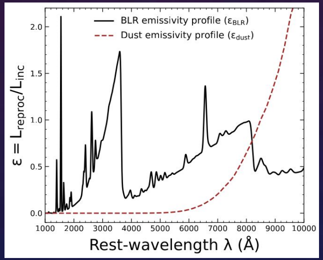
FAIRALL 9: results

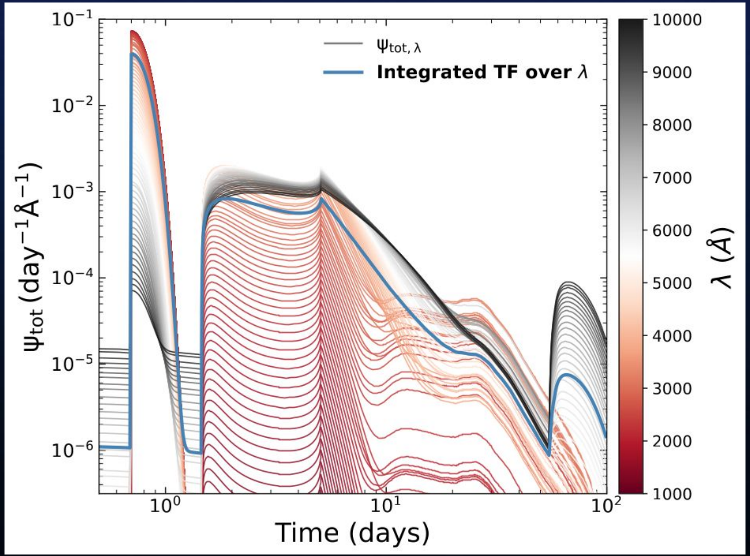


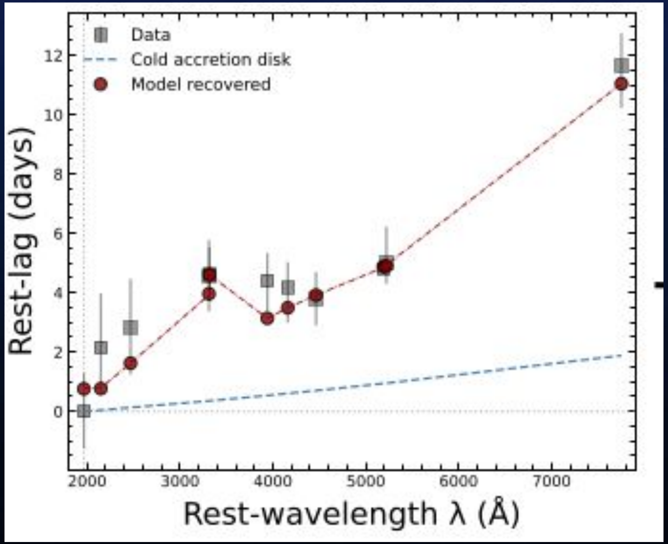




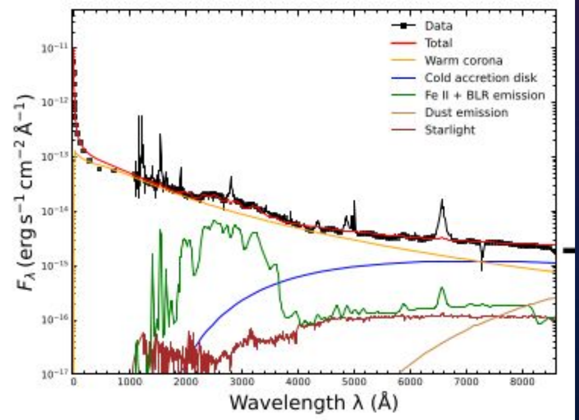


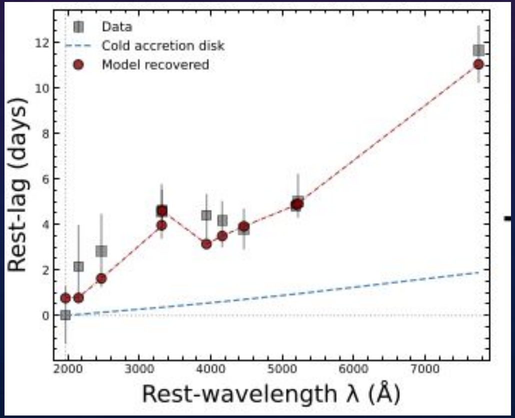


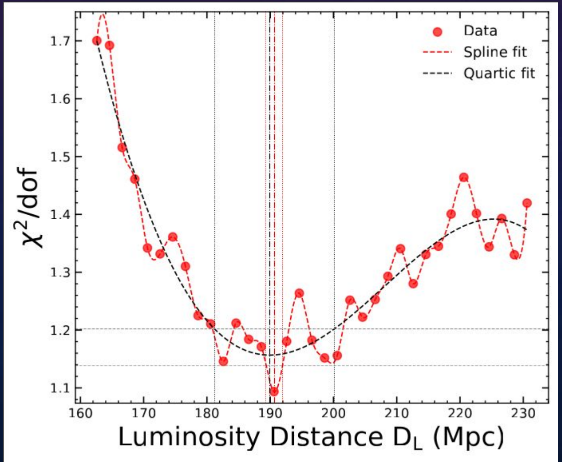




FAIRALL 9: Hubble constant



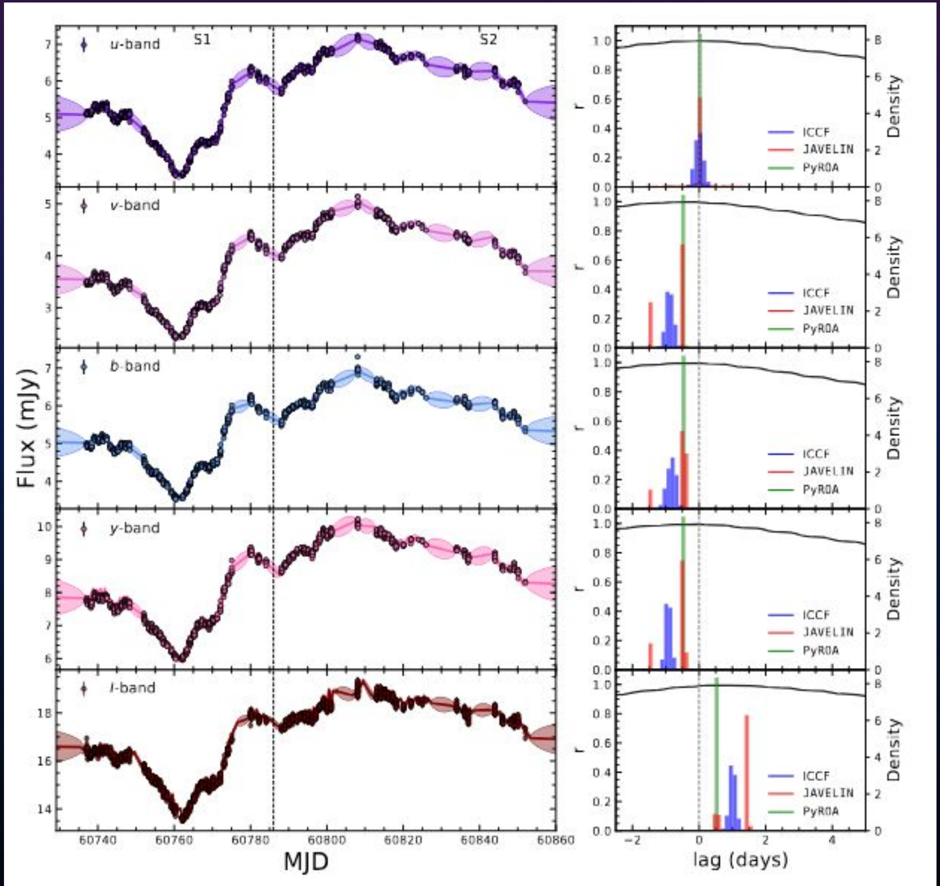


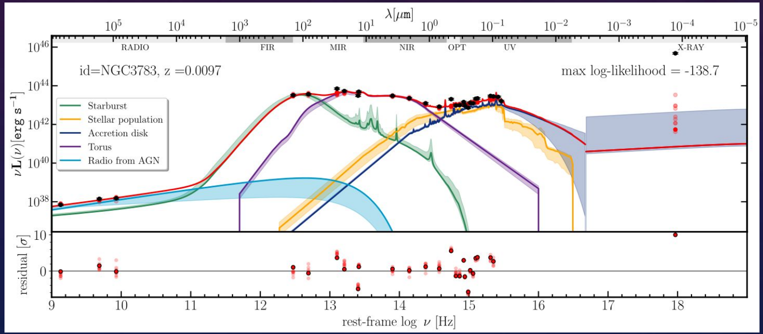


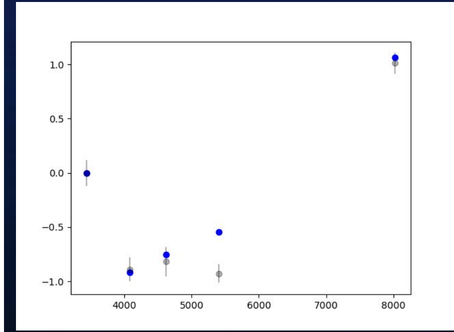
D_L = 189.9 (-8.7 / +10.2) Mpc
z = 0.04614
H_0 = 72.4 (-3.7 / +3.4) km/s/Mpc

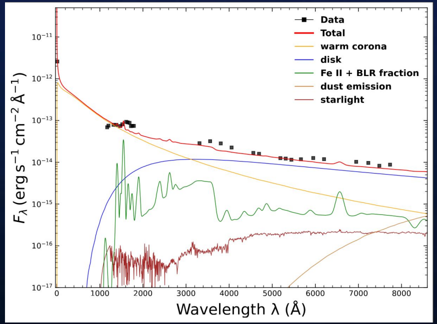
Mandal et al., 2026(HALO II: Submitted)

Preliminary results for NGC 3783









Conclusion

- ★ Comparison with our first attempt on NGC 5548:

fairall 9: H_0 = 72.4(-3.7/+3.4) km/s/Mpc
NGC 5548: H_0 = 74.1(-9.5/+9.2) km/s/Mpc (See Jaiswal et al., 2025, A&A, 702, 92 for NGC 5548)

- ★ Our estimated Hubble constant has 5-10 % uncertainty for a single source.
- ★ We have consistent results which highlight the potential of our approach to address the hubble constant tension with larger sample.

- ★ We aim to observe more sources with addition to those which have highly reliable time lag present in the literature.

Some highlights of Warsaw
credit: Pulkit Ojha

Thank you!